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ESTIMATION OF POND EVAPORATION IN THE GEORGIA COASTAL PLAIN

ARS-S-89
March 1976

AGRICULTURAL RESEARCH SERVICE • U.S. DEPARTMENT OF AGRICULTURE

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE
in cooperation with
Georgia Institute of Technology
Middle South Georgia Soil and Water Conservation District
University of Georgia College of Agriculture Experiment Stations

CONTENTS

Page

Abstract 1

Introduction 1

Procedures for estimating evaporation 1

- Weather Bureau method 2
- Penman model 2
- Modified fractional-evaporation equivalent method 2
- Fractional-evaporation equivalent method 2
- Linear regression with meteorological factors 2

Results of data analysis 3

Sensitivity analysis 4

Factor analysis of pan evaporation and meteorological data 5

Conclusions 6

Literature cited 7

TABLES

1. Comparison of computed and observed evaporation rates 3
2. Monthly relative sensitivity values for Tifton, Ga. 4
3. Correlation matrix 5
4. Eigenvalues and corresponding eigenvectors 5

ESTIMATION OF POND EVAPORATION IN THE GEORGIA COASTAL PLAIN

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ABSTRACT

Various techniques to estimate pond evaporation are compared on the basis of their ability to reproduce observed evaporation rates from a floating pan. Methods that use only one meteorological factor provided correlation coefficients that were only slightly smaller than those obtained with methods requiring values for two to four meteorological factors. Factor analysis indicated that radiation, humidity, and air temperature have similar effects on the variation in floating-pan evaporation; thus, it is not necessary to use all three factors for predicting evaporation rates. Correlation analysis, sensitivity analysis, and factor analysis indicated that variation in air speed has little effect on variation in evaporation.

INTRODUCTION

The mean annual rainfall for the 48-year period 1923–70 recorded at the Coastal Plain Experiment Station, Tifton, Ga., was 47.24 inches. This was well distributed, with the months of October and November showing the lowest average rainfall of 1.93 inches and July the highest of 6.03 inches. However, mean monthly rainfall is misleading because there are several drought periods during the crop-growing season each year. Storage of sufficient water to meet irrigation requirements is the obvious solution; hence, estimates of pond evaporation in the Georgia Coastal Plain are necessary for estimation of pond storage requirements.

The net evaporation rate is controlled by the meteorological conditions of the overlying air and the energy state of the evaporating surface layer. The quantity of thermal energy stored in a pond or lake can also be a controlling factor during certain periods of the year. Evaporation rates from open water surfaces have been estimated from measurements of water losses from pans (*16*)[3] and sunken tanks (*1*), by using models developed from energy budgets (*13*), and by empirical analysis of data (*9*). Methods that require measurements of water surface properties are rarely used because water surface data are difficult and expensive to collect. Thus, most evaporation estimation procedures are based on data that can be collected above the water surface.

Hydrologic models are potentially useful for predicting the output from a hydrologic process and for identifying the relative importance of variables that influence the hydrologic process being modeled. If the only objective of modeling is prediction, it may be reasonable to structure a model on only those variables that contribute statistically significant, physically meaningful information. Numerous methods involving meteorological factors as predictor variables have been proposed for estimating evaporation rates. However, past investigations have not identified the marginal value of different meteorological factors for predicting evaporation rates. In this study a sensitivity analysis, a factor analysis, and a correlation analysis were used to examine the marginal value of four meteorological factors (radiation, air speed, relative humidity, and air temperature) for predicting evaporation rates in the Georgia Coastal Plain.

PROCEDURES FOR ESTIMATING EVAPORATION

Numerous methods have been proposed for estimating evaporation. The prediction methods examined herein are classified according to the data required to estimate evaporation and whether or not the method requires empirical calibration of structural coefficients. The following three methods, none of which requires the estimation of structural coefficients, were examined: the U.S. Weather Bureau[4] method (WB), the Penman method, and a modified fractional-evaporation equivalent method (MFEE). Additionally, the fractional-evaporation equivalent method (FEE) and four linear bivariate regression equations were calibrated from observed data and then were used to predict daily evaporation.

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[3] Italic numbers in parentheses refer to items in "Literature Cited" at the end of this publication.

Weather Bureau Method

The WB method of estimating evaporation was developed by Kohler, Nordenson, and Fox (*7*) from an extensive analysis of data. The WB method requires observations of air temperature (T), radiation (R), humidity (H), and air speed (V). The method was originally presented in nomograph form; Lamoreux (*8*) provided the following functional representation:

$$E = e^{[(T-212)(0.1024-0.1066 \ln_e R)]} - 0.0001 \\ +0.025\,(e_s - e_a)^{0.88}(0.37 + 0.0041V) \\ \times [0.025+(T+398.36)^{-2}\,(4.7988\times 10^{10})\,e^{[-7482.6/(T+398.36)]}]^{-1} \quad (1)$$

Here, e_s and e_a are the vapor pressures at dew point temperature and air temperature, respectively.

Penman Model

In a simplified form, an energy balance equates the net radiant-heat flux density (R_n) to the sum of the latent heat of evaporation (E) and the flux density of sensible heat (S),

$$R_n = E + S. \quad (2)$$

From aerodynamic considerations of turbulent transfer, the latent heat flux density is given by a form of Dalton's law,

$$E = f_o\,(V)\,(e_o - e_a), \quad (3)$$

and the sensible heat transfer is given by

$$s = \gamma f_o\,(V)\,(T_o - T_a), \quad (4)$$

where γ is the psychrometric constant, $f_o\,(V)$ is a wind function, e is the vapor pressure, T is the temperature, and the subscripts o and a refer to water surface and air quantities, respectively. Equations 2, 3, and 4 are the basis for the Penman model (*13*, *14*), given by

$$E_o = (\Delta \cdot R_n + \gamma \cdot E_{ao})\,/\,(\Delta + \gamma), \quad (5)$$

where E_o is the evaporation estimate and Δ is the slope of the saturation vapor pressure curve at air temperature (T_a). E_{ao} is an empirical representation of the latent heat flux density given by

$$E_{ao} = 0.35\,(0.5 + V/100)\,(e_o - e_a), \quad (6)$$

where V is the air speed in miles per day. Stanhill et al. (*18*) showed that the ratio of net radiation to incoming solar radiation was approximately 58 percent for a small pond in Israel at approximately the same latitude as Tifton, Ga. Monteith and Szeicz (*12*) calculated a net radiation ratio of 0.53 for an open water surface. Davies (*4*) indicated that net radiation (R_n) is, on the average, 55 percent of the measured radiation (R). Thus, E_0 in equation 5 can be approximated by

$$E_o = [0.55 \cdot \Delta \cdot \mathrm{R} + \gamma \\ \cdot 0.35\,(0.5 + V/100)(e_o - e_a)]/(\Delta + \gamma). \quad (7)$$

Modified Fractional-Evaporation Equivalent Method

The MFEE method given by Linacre (*10*) relates the fraction of insolation (E/R) used for evaporation with the mean daily ambient temperature T_c, in degrees centigrade, and the fraction relative humidity H by the following empirical nonlinear equation:

$$E/R = 0.02 \cdot H \cdot T_c + 0.9 - H. \quad (8)$$

Linacre indicated that the coefficient 0.02 agrees favorably with values derived empirically for evaporation from grass surfaces. Although the coefficient for water surfaces would probably be smaller, a value for water was not available, and the coefficient 0.02 is used herein.

Fractional-Evaporation Equivalent Method

The FEE method relates the fraction of insolation used for evaporation to air temperature (T_a) by the linear equation

$$E/R = g + fT_a, \quad (9)$$

where E and R are evaporation and radiation, respectively, and f and g are regression coefficients. The FEE method has been used by Stephens and Stewart (*19*) in southern Florida and Lane (*9*) in the Western United States. Values of the regression coefficients were determined empirically for this study from the analysis of radiation, temperature, and pan evaporation data.

Linear Regression With Meteorological Factors

The following linear regression equation was used to relate individually each of the four meteorological factors (radiation, air speed, air temperature, and relative humidity) to daily pan evaporation rate E:

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[4] Now U.S. Weather Service.

$$E = a + bF, \tag{10}$$

where F is the meteorological factor and a and b are the regression coefficients. The regression coefficients were derived from the observed evaporation from a floating pan as the criterion variable.

RESULTS OF DATA ANALYSIS

The Southeast Watershed Research Unit (Agricultural Research Service) is conducting hydrologic studies at a pond on the J. B. Walker farm, 5 miles southwest of Tifton, Ga. Walker Pond has a maximum storage of 9.81 acre-feet and a maximum surface area of 2.56 acres. Daily evaporation is measured from a pan floating on the pond. The floating pan is partially shielded by a group of trees. The average tree height in the woodland (pine) east of the evaporation pan is 25 feet. There are about 650 trees per acre in this plot.

Meteorological data, including relative humidity, air temperature, air speed, and incoming radiation, are measured at the U.S. Weather Service office in Tifton, Ga. During fall and winter, the prevailing winds are from the northwest and northeast. During the remainder of the year, the prevailing winds are from the west and southwest. During a 33-month period, 392 daily measurements of evaporation from the floating pan and the four meteorological factors from the Weather Service office were made.

Estimates of daily evaporation were derived by each of the previously described methods from the 392 daily measurements of the 4 meteorological factors and floating-pan evaporation data. The computed evaporation rates were compared with the corresponding measured values. The Pearson product-moment correlation coefficient R was used as a measure of the strength of the linear association between the observed and computed evaporation rates. The coefficient of determination R^2 is the proportion of the variance in the observed evaporation rates that can be attributed to its association with the computed rates. The resulting values of R and R^2 are given in table 1.

TABLE 1.—*Comparison of computed and observed evaporation rates*

Procedure	R	R^2
Weather Bureau	0.650	0.423
Penman	.626	.393
Modified fractional-evaporation equivalent	.623	.388
Fractional-evaporation equivalent	.579	.334
Linear regression: Predictor variable:		
Humidity	−.620	.385
Radiation	.567	.322
Temperature	.559	.312
Air speed	−.122	.015

The bivariate linear regression equations involving humidity, radiation, air temperature, and air speed explained 38.5, 32.2, 31.2 and 1.5 percent of the total variation in the observed daily evaporation, respectively. The inadequacy of the air speed measurements for estimating evaporation is demonstrated by the negative value of the correlation coefficient. A negative value of R for such a relationship indicates that increases in air speed are accompanied by decreases in evaporation. Such a result would not be expected.

The FEE method, which uses two meteorological factors (radiation and air temperature) to estimate evaporation, explained 33.4 percent of the total variation, only 1.2 and 2.2 percent greater than the percentage of variation explained by the bivariate regression equations for radiation and air temperature. This suggests that radiation and air temperature are intercorrelated and tends to explain similar variation in evaporation rates.

The MFEE method, equation 8, explained 38.8 percent of the total variation in the observed evaporation rates, which is only 0.3 percent greater than the value resulting from the bivariate regression equation for humidity. However, the coefficients for the bivariate regression equation involving humidity were derived from data collected at Tifton, Ga., while the coefficients for the MFEE method were from the developments of a previous investigator (*10*). Thus, the difference of 0.3 percent in explained variation is not necessarily an indication that humidity, air temperature, and radiation explain similar variation in evaporation. Also, the coefficients of the MFEE method are possibly inadequate for estimating evaporation from ponds in the southern Coastal Plain.

The WB and Penman methods, which require values of four meteorological factors, explained 42.3 and 39.3 percent of the total variation, respectively. The MFEE method, which involves only three meteorological variables and does not require calibration of structural coefficients, explained 38.8 percent of the variation. Thus, air speed, which is used with the WB and Penman methods but not the MFEE method, does not significantly increase the percentage of explained variation. Such a result was expected, since the correlation coefficient for the bivariate regression equation involving air speed was very small and not statistically significant.

Even though the structural coefficients for the bivariate regression equation involving humidity were derived from observed data, this equation explained only 3.8 and 0.8 percent less variation than the WB and Penman methods, respectively. Thus, it is reasonable to examine the possibility that measurements of radiation, air temperature, and humidity explain similar variation in evaporation measurements and that the collection of data for all three meteorological factors represents a duplication of information and effort for prediction of evaporation rates; a factor analysis will be used to examine the intercorrelations of the meteorological variables in a later section.

SENSITIVITY ANALYSIS

Correlation coefficients are used to measure the degree of association between variables. The Pearson product-moment correlation coefficient is defined by

$$R=\sum_{i=1}^{n} x_i y_i \ / \ \left(\sum_{i=1}^{n} x_i^2 \sum_{i=1}^{n} y_i^2\right)^{0.5}, \tag{11}$$

where $x=X-\bar{X}$, $y=Y-\bar{Y}$, and n is the number of x,y pairs. The square of the correlation coefficient represents the proportion of the variance in a criterion Y that can be attributed to its linear regression on a predictor X.

Regression analysis is used to define the relationship between variables. There is a strong structural similarity between correlation analysis and regression analysis (*17*). The linear regression coefficient b can be computed from the correlation coefficient and the standard deviation of X and Y:

$$b=\sum_{i=1}^{n} x_i y_i \ / \ \sum_{i=1}^{n} x_i^2 = RS_y/S_x. \tag{12}$$

Equation 12 suggests that for values of R near 1, changes in X will produce comparatively large changes in Y.

The sensitivity of evaporation to a meteorological factor is defined as the rate of change in evaporation with respect to change in the meteorological factor. For a linear regression equation relating evaporation E and a meteorological factor F, the sensitivity of E to variation in F can be determined by taking the derivative of E with respect to F:

$$dE/dF=b. \tag{13}$$

Equations 12 and 13 show that there is a direct relationship between linear regression and sensitivity. Therefore, estimates of sensitivity can be used to determine a priori the factors that might account for the most variation in the dependent variables.

The value of sensitivity computed by the derivative approach of equation 13 is not invariant to the magnitude of either the dependent or independent variable. Relative sensitivity R_s is defined as the ratio of the percentage change in evaporation $(\Delta E/E)$ to the percentage change in the magnitude of the meteorological factor $(\Delta F/F)$:

$$R_s=\frac{\Delta E/E}{\Delta F/F}=\left(\frac{\Delta E}{\Delta F}\right)\left(\frac{F}{E}\right). \tag{14}$$

Since the relative sensitivity is a function of F and E, it can be used for comparing the sensitivity of the different meteorological factors that influence evaporation. A negative value of R_s indicates that as the value of the meteorological factor increases evaporation will decrease.

In order to relate relative sensitivity values to the influence of the meteorological factors in estimating evaporation rates, it is necessary to specify a model of the evaporation process from which R_s values can be derived. Use of a model based on the underlying physical principles will provide R_s values that are indicative of the relative influence of variables in the evaporation process. Thus, the Penman model was selected because it is based on a simplified energy balance equation. With average monthly values (*20*) of meteorological factors and the Penman model, monthly values of relative sensitivity were determined (table 2).

The mean annual relative sensitivity values for the four meteorological factors indicate that humid-

TABLE 2.—*Monthly relative sensitivity values for Tifton, Ga.*

Month	Mean daily evaporation (inch/day)	Relative sensitivity of the meteorological factor			
		Humidity	Air speed	Radiation	Temperature
Jan.	0.082	−1.034	0.256	0.655	0.661
Feb.	.101	−.811	.258	.652	.688
Mar.	.132	−.672	.224	.698	.637
Apr.	.172	−.569	.199	.732	.621
May	.196	−.542	.189	.745	.627
June	.199	−.521	.158	.777	.589
July	.184	−.641	.128	.819	.484
Aug.	.180	−.656	.131	.815	.495
Sept.	.148	−.763	.152	.785	.554
Oct.	.119	−.805	.189	.732	.629
Nov.	.092	−.846	.232	.671	.677
Dec.	.073	−1.184	.277	.626	.717
Mean		−.753	.199	.726	.615

ity is the most sensitive factor and that radiation and temperature are slightly less sensitive. The mean R_s value for air speed indicates that a 10-percent change in air speed produces a 2-percent change in evaporation. Linsley, Kohler, and Paulhus (*11*) indicated that a 10-percent change in air speed causes a change in evaporation of 1 to 3 percent. Thus, the relative sensitivity values derived herein appear reasonable. A ranking of the mean sensitivity of the four factors corresponds exactly to the ranking of correlation coefficients for the bivariate regression equations of table 1. In both rankings, there is a very noticeable difference between air speed and the three remaining meteorological factors.

The monthly R_s values of table 2 indicate that evaporation rates are most sensitive to variation in humidity during winter. During summer, variation in radiation produces a greater change in evaporation than does variation in humidity. From April to June, both temperature and radiation are more sensitive than humidity. Thus, the values of relative sensitivity are potentially useful for indicating the relative importance of the factors that control the evaporation process and the contribution of each factor in the reproduction of measured evaporation rates.

FACTOR ANALYSIS OF PAN EVAPORATION AND METEOROLOGICAL DATA

Factor analysis, a multivariate statistical technique, can be used to examine the intercorrelations between the observed meteorological and pan evaporation data. Such an analysis is desirable because it can lead to a reduction in the number of "independent" variables required to predict a "dependent" variable. Elimination of predictor variables that explain similar variation in the criterion can reduce the cost of future data collection. A reduction in the number of predictor variables may reduce prediction ability somewhat, but for variables that are highly intercorrelated, the reduction is often insignificant.

Factor analysis transforms the correlation matrix of the criterion and predictor variables into a set of variates called factors. These factors are linear combinations of the original variables and have the advantage of being uncorrelated. The coefficients of the factors are called factor loadings.

The correlation matrix of table 3 was derived from 392 daily measurements of four meteorological factors and evaporation from a floating pan. With the exception of associations involving air speed, the correlation coefficients between each pair of variables exceeded 0.5. The correlation coefficients between air speed and each of the other four variables are between zero and −0.3. But the correlation matrix by itself does not provide the means for determining whether or not the four variates other than air speed explain similar information.

A factor analysis of the correlation matrix of table 3 produced the eigenvalues and factor pattern of table 4. In the first factor all of the factor loadings are large except the factor loading for air speed. The factor loading for air speed is large in the second factor while the other four factor loadings are small. In the remaining three factors, all the loadings are comparatively small.

TABLE 3.—*Correlation matrix*

Variable	Pan evap. (1)	Temp. (2)	Air speed (3)	Radiation (4)	VPD (5)
(1) Pan evaporation	1.0000	0.5587	−0.1224	0.5667	0.6203
(2) Temperature	.5587	1.0000	−.2914	.5282	.8240
(3) Air speed	−.1224	−.2194	1.0000	−.1981	−.2939
(4) Radiation	.5667	.5282	−.1981	1.0000	.7237
(5) Vapor pressure deficit (VPD)	.6203	.8240	−.2939	.7237	1.0000

TABLE 4.—*Eigenvalues and corresponding eigenvectors*

Variable	Eigenvalues for eigenvector of—				
	3.01 (1)	0.93 (2)	.049 (3)	.044 (4)	.013 (5)
(1) Pan evaporation	0.779	0.224	−0.305	−0.491	0.002
(2) Temperature	.854	.057	.478	−.051	.190
(3) Air speed	−.358	.925	.089	.085	−.021
(4) Radiation	.817	.101	−.366	.420	.110
(5) Vapor pressure deficit	.937	.011	.171	.121	−.279

Although methods exist for determining the number of statistically significant factors (*2*, *3*, *15*), a universally accepted standard for when to stop factoring has not been developed (*5*). Furthermore, information, even though statistically significant, may have no practical value (*5*). Therefore, a method proposed by Kaiser (*6*) through extensive data analysis was used to determine the number of significant factors. Kaiser recommended that the factors corresponding to eigenvalues of the correlation matrix that are greater than 1 could be considered significant.

The eigenvalues of table 4, determined by Kaiser's method, indicate that only the first factor is significant. The large factor loadings in the first factor, which correspond to radiation, vapor pressure deficit, air temperature, and pan evaporation, suggest that observations of the three meteorological and pan evaporation variables contain similar information even though the four variables are dissimilar. If the three meteorological factors explain similar variation in pan evaporation, then a prediction equation including more than one of the three meteorological factors should not be expected to provide significantly greater correlation than a prediction equation involving only one of the variables. Comparison of the correlation coefficients of table 1 confirms the findings of the factor analysis and indicates that the methods involving more than one meteorological factor provide correlation coefficients only slightly higher than those obtained with the bivariate regression equations. Furthermore, the very low correlation between air speed and evaporation supports Kaiser's empirical rule for determining the number of significant factors. The sensitivity analysis also indicated that variation in air speed had little effect on variation in evaporation rates.

CONCLUSIONS

Since true rates of evaporation from the pond surface were not available, the observed floating-pan evaporation rates are used to represent them. Such an assumption seemed reasonable since the mean annual evaporation from the floating pan was only about 9 percent less than the annual rate reported for the Tifton area by the U.S. Department of Commerce (*20*). During fall and winter, air moves primarily out of the northwest and northeast. The wooded area north of Walker Pond could significantly influence evaporation rates and thus account for, in part, the difference between the observed and computed mean annual evaporation. The mean observed May-to-October evaporation expressed as a percentage of the total annual evaporation differed from the reported evaporation by only 2 percent. From May to October the wind moves primarily from the west and southwest. During this period the wooded area on the northern bank of the pond would not significantly influence evaporation rates. Furthermore, a recent study (*1*) indicated that the average ratio of evaporation from Lake Hefner to evaporation from tanks with diameters of 9 and 15 feet and located approximately 100 feet from the lake is 1.01.

As indicated previously, an understanding of the evaporation process can provide the means for obtaining better estimates of evaporation rates. Such estimates of evaporation can then be used to provide more accurate estimates of the storage required for irrigation supplies during drought. A sensitivity analysis was used to examine the relative importance in the Georgia Coastal Plain of four meteorological variables thought to influence evaporation. Mean annual relative sensitivity values indicated that humidity, radiation, and air temperature are of similar importance, while variation in air speed has a much smaller influence on evaporation rates. However, mean monthly relative sensitivity values indicated that humidity is the controlling factor in winter, while radiation exerts a greater influence on evaporation rates in summer.

The correlation analysis of table 1 indicates that the WB method is potentially capable of providing the best estimates of evaporation. If a method for estimating net radiation is available, the Penman method also provides reasonable estimates of daily evaporation. However, the correlation coefficients obtained with three of the bivariate regression equations were only slightly less than the correlation coefficients obtained with the WB and Penman equations; this suggests that the use of more than one meteorological factor is redundant when the objective of modeling is prediction.

Whereas the coefficients of the WB and Penman methods were derived at other locations, the regression coefficients for the bivariate regression equations were derived from data collected at Tifton, Ga. Therefore, a factor analysis was used to examine the intercorrelations between the meteorological factors and floating-pan evaporation rates. The factor analysis supported the conclusions of the correlation analysis. Specifically, the factor analysis indicated that radiation, air temperature, vapor pressure deficit, and pan evaporation explain similar variation, and thus, for the Georgia Coastal Plain, the use of more than one of the three meteorological factors (vapor pressure deficit, radiation, and air temperature) may be redundant for predicting evaporation.

The correlation analysis, sensitivity analysis, and factor analysis indicated that evaporation rates are only slightly influenced by variation in air speed. The sensitivity analysis showed that a variation in air speed of 10 percent results in a 2-percent change in evaporation. Thus, the very low correlation coefficient, −0.122, between air speed and pan evaporation should have been expected. The factor analysis also indicated that air speed was not a significant factor in estimating floating-pan evaporation.

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*1796-G.P.O.-1750-s/671-583/46

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